

Pre- and Postprocedural CT of Transcatheter Left Atrial Appendage Closure Devices

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Abbreviations: LA = left atrium, LAA = LA appendage, LAAC = LAA closure, LSPV = left superior pulmonary vein, TEE = transesophageal echocardiography, 3D = three-dimensional, 2D = two-dimensional

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SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- Identify the role of CT in the evaluation of patients for transcatheter left atrial appendage (LAA) closure (LAAC).
- Describe the optimal CT protocol for pre- and postprocedural evaluation for transcatheter LAAC.
- Discuss the common postprocedural complications of LAAC.

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Transcatheter left atrial appendage (LAA) closure is an alternative to long-term anticoagulation therapy in selected patients with non-valvular atrial fibrillation who have an increased risk for stroke. LAA closure devices can be implanted by means of either an endocardial or a combined endocardial and epicardial approach. Preprocedural imaging is key to identifying contraindications, accurately sizing the device, and minimizing complications. Transesophageal echocardiography (TEE) has been the reference standard imaging modality to assess the anatomy for LAA closure and to provide intraprocedural guidance. However, CT has emerged as a less-invasive alternative to TEE for pre- and postprocedural imaging. CT is comparable to TEE for exclusion of thrombus but is superior to TEE for the delineation of complex LAA anatomy, measurement for device sizing, and evaluation of pulmonary venous and extracardiac structures. CT provides accurate measurements of the LAA ostial diameter, landing zone diameter, and LAA length, which are vital for accurate sizing of the device. CT allows evaluation of the relationship with the pulmonary veins and other adjacent structures that can be injured during the procedure. CT also simulates procedural fluoroscopic angles and provides evaluation of the interatrial septum, which is punctured during LAA closure. CT also provides a more convenient method for the evaluation of postprocedural complications such as incomplete closure, peridevice leaking, device-related thrombus, and device dislodgement.

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Introduction

Patients with atrial fibrillation have a fivefold higher risk of stroke due to thromboembolism when compared with healthy patients (1,2). The left atrial (LA) appendage (LAA) is the source of a thrombus in up to 91% of patients with nonvalvular atrial fibrillation (3), which results in poor LA contractility, increased blood stasis, increased thrombogenicity, and LA remodeling (4). Oral anticoagulants including warfarin and direct agents such as rivaroxaban and apixaban are the first-line therapy for prevention of stroke in these patients. However, many patients with nonvalvular atrial fibrillation are not eligible to take lifelong anticoagulation medications because they have a prohibitive risk of bleeding or other medical conditions. Furthermore, less than 50% of patients who are prescribed anticoagulation therapy are found to be adherent to therapy at 1 year (5).

Transcatheter LAA closure (LAAC) has emerged as a feasible alternative to address the unmet clinical need for prevention of stroke in selected patients with nonvalvular atrial fibrillation. Landmark randomized controlled trials PROTECT AF (Watchman Left Atrial Appendage System for Embolic Protection in Patients with Atrial Fibrillation) and PREVAIL (6) were instrumental in the determination of procedural

TEACHING POINTS

- Transcatheter LAAC closure (LAAC) has emerged as a feasible alternative to address the unmet clinical need for prevention of stroke in selected patients with nonvalvular atrial fibrillation.
- CT is comparable to TEE for evaluation of a thrombus but is superior to TEE for providing comprehensive information on the complex and variable size and shape of the LAA, for accurate device sizing, and for evaluation of extracardiac structures.
- A thrombus in the LAA is an absolute contraindication for LAAC.
- For the Watchman device, the length of the dominant lobe is measured from the landing zone plane to the tip of the dominant lobe.
- At CT, a normal LAAC device is seated in the LAA and sealed to its wall, without any rotation around its central axis.

success and the safety of transcatheter LAAC (7). The efficacy of LAAC was further supported in several observational studies (7–10). As a result, transcatheter LAAC for prevention of stroke has been assigned a Class IIb recommendation, with a level of evidence of B per the 2019 American Heart Association, American College of Cardiology, and Heart Rhythm Society guidelines for the management of nonvalvular atrial fibrillation (11).

LAA Anatomy

The LAA is a fingerlike extension of the anterolateral LA that is located in the left atrioventricular groove between the pulmonary trunk superiorly and the left ventricle inferiorly. The LAA has three regions: the ostium, which is the opening from the LA; the neck; and the body (Fig E1). The LAA has one or more lobes, which are patent outpouchings from the main body that are demarcated by an external crease. These lobes may be located in a different plane or direction than that of the body (12). The LAA has a thin wall (approximately 1 mm) and a rough internal surface because of thick (>1 mm) pectinate muscles or trabeculations. This reflects the development of the LAA from the primordial LA, unlike the smooth-walled LA, which develops from the outgrowth of pulmonary vein buds from the lungs (4). The LAA has contractility and quadriphasic blood flow in a normal rhythm, which are impaired in patients with atrial fibrillation.

Transcatheter LAAC Devices

Several transcatheter LAAC devices are available, each with a different deployment approach, anchoring mechanism, and anchoring position (Table E1) (Fig 1). These devices can be placed by means of either an endocardial or a hybrid endocardial-epicardial approach (Fig 2, Fig E2). The hybrid devices have the advantage of not requiring anticoagulation therapy after the pro-

cedure. The Watchman FLX (Boston Scientific), Amplatzer Cardiac Plug (Abbott), Amplatzer Amulet (Abbott), Wavecrest (Coherex), Lambre (Lifetech Scientific) and Ultrasept (Cardia) are examples of endocardial devices. The Amplatzer Cardiac Plug and Amulet have an anchoring lobe and a proximal occluder; other devices are anchored only by occluders with fixation barbs. Commonly used hybrid endocardial-epicardial devices include the Lariat (SentreHeart) and Sierra (Aegis Medical). Only some of these devices, such as the Watchman FLX and Lariat devices, are approved by the U.S. Food and Drug Administration (FDA) (7,8,10,13).

Role of Imaging in Transcatheter LAAC Planning

The main goals of preprocedural imaging in transcatheter LAAC are to evaluate for contraindications, assess the shape of the LAA, size the device accurately, and minimize procedural manipulations and complications. The ideal LAAC procedure uses one catheter, one device, and one deployment. Transesophageal echocardiography (TEE) is the established standard for preprocedural imaging for LAAC. TEE adequately allows exclusion of an intracardiac thrombus, evaluation of LAA size and shape, characterization of the atrial septum for transseptal puncture, and characterization of any pericardial effusion (14). Nonetheless, TEE is an invasive procedure, requires sedation, and is often not well tolerated by elderly patients. MRI is equally effective as TEE in the evaluation of cardiac thrombi (15), but limited data on its use for LAAC preprocedural evaluation exist (16). Lower spatial resolution and longer examination times are the challenges of MRI.

CT for Planning of Transcatheter LAAC

CT has emerged as an important imaging modality in preprocedural evaluation for transcatheter LAAC. High isotropic spatial resolution, good temporal resolution, a large field of view, multiplanar reconstruction capabilities, and rapid turnaround time are the strengths of CT. CT is comparable to TEE for evaluation of a thrombus but is superior to TEE for providing comprehensive information on the complex and variable size and shape of the LAA, for accurate device sizing, and for the evaluation of extracardiac structures. Unlike TEE, CT is a noninvasive technique and does not require sedation.

CT Protocol

A multidetector CT scanner with at least 64 detector rows is required for a high-quality scan.

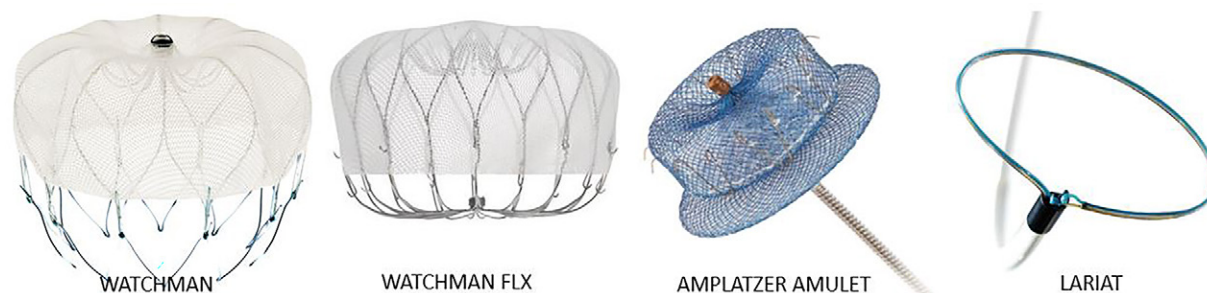


Figure 1. Commonly used transcatheter LAAC devices. Endocardial devices include the Watchman, Watchman FLX, and Amplatzer Amulet. The Lariat is the commonly used combined endocardial-epicardial device.

Oral hydration with 500 mL of water can be given to the patient before image acquisition to increase LA preloading. The scan is most commonly performed with retrospective electrocardiographic gating because of dynamic changes in the size of the LAA during the cardiac cycle (17,18). Some centers perform prospective electrocardiographic triggering in the ventricular systolic phase. A biphasic protocol of contrast material injection is used. Bolus tracking in the ascending aorta is used to trigger the imaging acquisition. Images are acquired from the carina to the diaphragm at expiratory breath hold. An additional delayed phase scan is performed through the heart 60 seconds after the arterial phase, either with prospective electrocardiographic gating or helical high-pitch acquisition to evaluate for a thrombus. Further details are provided in Table E2.

Critical Preprocedural CT Parameters

Evaluation of Contraindications.—A thrombus in the LAA is an absolute contraindication for LAAC. Patients with atrial fibrillation have an inherent increased risk of a thrombus. In addition, they may also have a pacemaker or defibrillator, which is prone to thrombus formation and can serve as a potential source for paradoxical embolism across the site of transseptal puncture. At CT, an LAA thrombus is seen as a well-defined hypoattenuating filling defect. A similar appearance may be seen owing to incomplete mixing of contrast material and blood because of slow flow (19). A thrombus generally shows lower attenuation (<100 HU) than that of slow flow and persists during the delayed phase, whereas slow flow does not persist (Fig 3). Combined arterial and delayed phase CT has higher accuracy for detection of a thrombus compared with that of TEE (sensitivity, 100%; specificity, 99%; positive predictive value, 92%; negative predictive value, 100%) (20). Other CT strategies for distinguishing a thrombus from

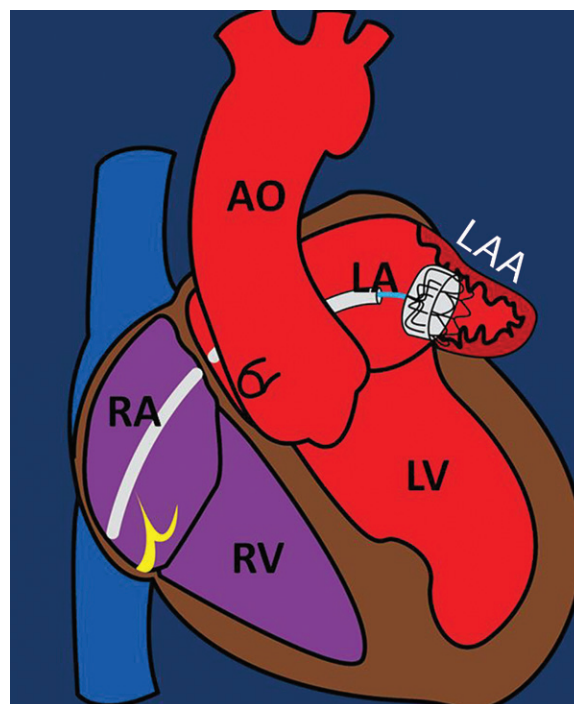


Figure 2. Schematic illustration of the endocardial LAAC approach. A sheath is introduced through the femoral vein and advanced to the right atrium (RA). Through a transeptal puncture, the sheath is advanced to the LA, where the device is deployed under fluoroscopic and echocardiographic guidance. AO = aorta, LV = left ventricle, RV = right ventricle.

slow flow include imaging with the patient in a prone position, reconstructing an iodine map from spectral CT data, and using contrast material injection techniques such as a split bolus or double injection (21–24).

Specific to hybrid LAAC techniques, pericarditis and pericardial adhesions from previous surgery or radiation are contraindications. At CT, pericardial thickening, calcifications, effusions, and contrast enhancement may be seen. Additional contraindications for epicardial techniques include pectus excavatum (Fig E3), a posteriorly rotated heart, and an LAA positioned behind the pulmonary trunk or adjacent to a coronary bypass graft (25) (Fig 4).

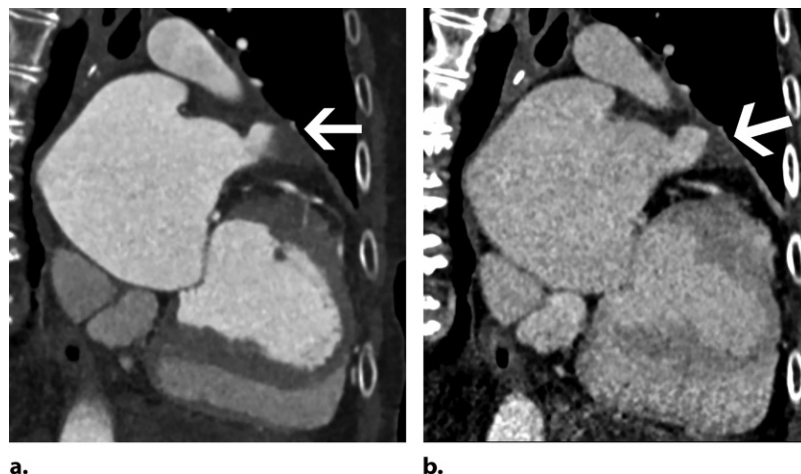


Figure 3. Contraindication for LAAC in a 63-year-old woman who was under evaluation for transcatheter LAAC. (a) Two-chamber reconstructed CT image shows a hypoattenuating filling defect (arrow) in the tip of the LAA. (b) Two-chamber reconstructed CT image obtained 60 seconds later shows persistence of the filling defect (arrow), which is consistent with a thrombus.

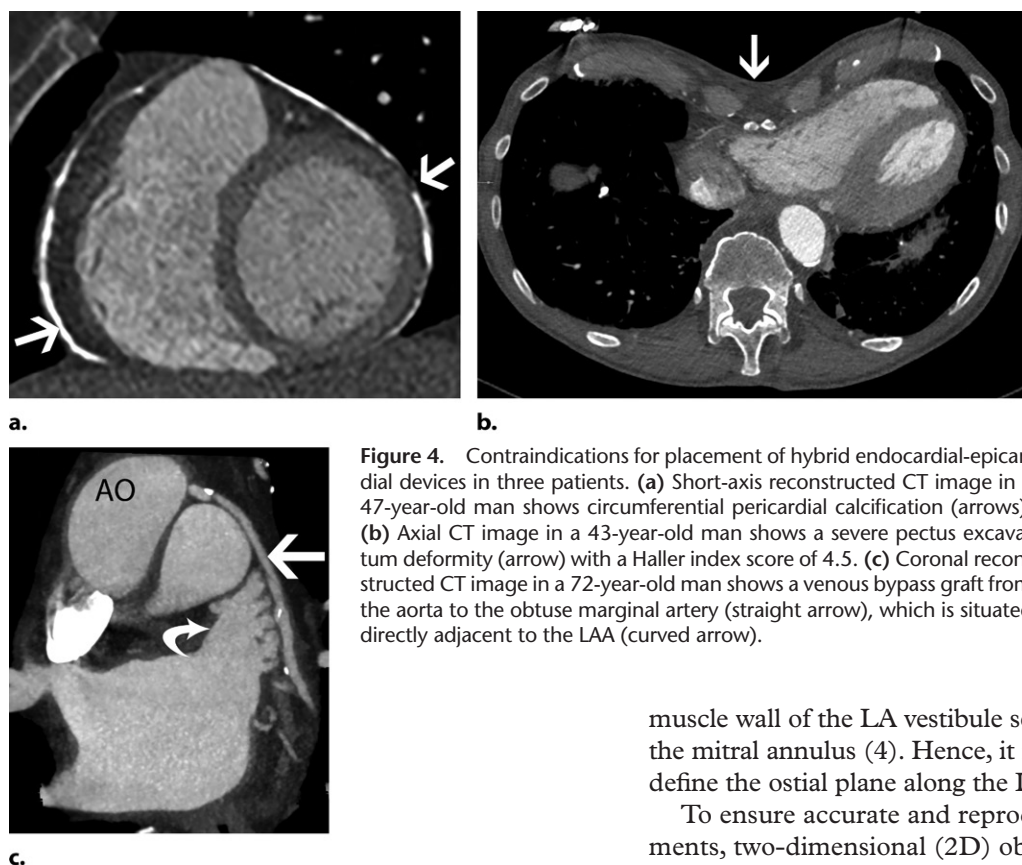


Figure 4. Contraindications for placement of hybrid endocardial-epicardial devices in three patients. (a) Short-axis reconstructed CT image in a 47-year-old man shows circumferential pericardial calcification (arrows). (b) Axial CT image in a 43-year-old man shows a severe pectus excavatum deformity (arrow) with a Haller index score of 4.5. (c) Coronal reconstructed CT image in a 72-year-old man shows a venous bypass graft from the aorta to the obtuse marginal artery (straight arrow), which is situated directly adjacent to the LAA (curved arrow).

LAA Measurements.—The LAA ostium, device landing zone, and LAA length are key determinants of sizing and seating an LAAC device. The LAA ostium is roughly planar and typically of an elliptical shape (ie, in 69% of patients) (4). Occasionally the ostium is round (6%), triangular (8%), shaped like a water drop (8%) or a foot (10%), or irregular (4,26,27). The ostium margins are well-defined posterosuperiorly by the tip of the Coumadin ridge, which is called the limbus and separates the ostium from the left superior pulmonary vein (LSPV) (28) (Fig 5). However, the ostium is ill-defined anteroinferiorly, where the smooth

muscle wall of the LA vestibule separates it from the mitral annulus (4). Hence, it is ambiguous to define the ostial plane along the LA vestibule.

To ensure accurate and reproducible measurements, two-dimensional (2D) oblique transverse measurement is recommended over 2D orthogonal or three-dimensional (3D) measurements (26). Since the LAA ostium size is dynamic (Movies 1, 2), ostium measurements are obtained during the cardiac phase at which the LAA ostium is the largest. This is typically in the ventricular end systolic phase (30%–40% R-R interval). From the axial CT images, an oblique section is created perpendicular to the long axis of the left circumflex artery. In this long-axis two-chamber view of the heart and the LAA, the ostium is defined as the plane between the left circumflex artery and the Coumadin ridge. An en-face view is generated at this location for measurement of maximal and minimal diameters, area, and

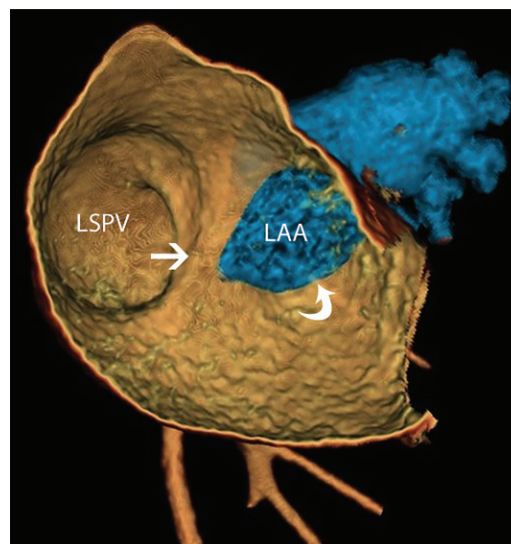


Figure 5. LAA ostium in a 59-year-old man. Oblique 3D volume-rendered endocardial view CT image of the LA (tan) shows that the extent of the ostium of the LAA (blue) is well defined at the posterior and superior aspect, where it is bordered by the Coumadin ridge (straight arrow) that separates the LAA ostium from that of LSPV. Anteroinferiorly, the ostium is ill-defined (curved arrow) at the region of the LA vestibule.

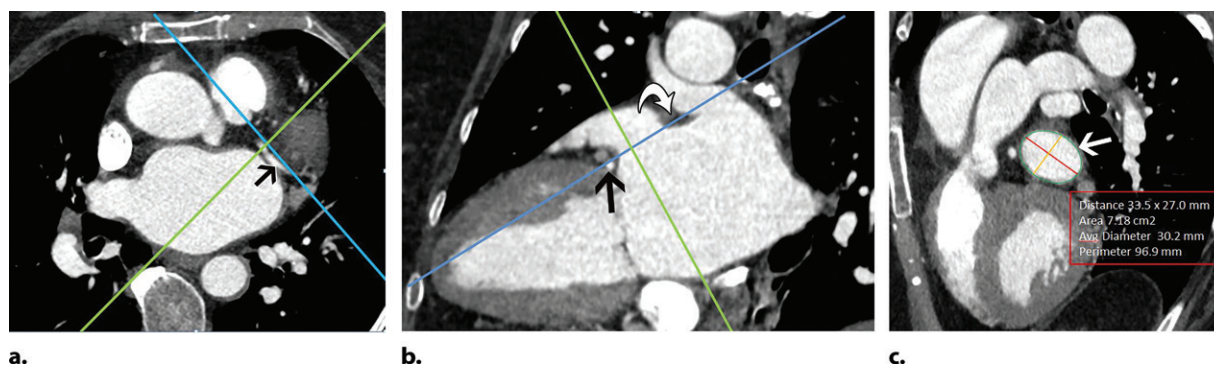


Figure 6. Measurement of LAA ostium. (a) Axial CT image of the heart is used to identify the left circumflex coronary artery (arrow). A plane that is perpendicular to the long axis of the left circumflex artery is identified. Multiplanar reformat axes are shown on the long-axis images (blue and green lines). (b) Long-axis-view CT image of the left ventricle and LAA shows the LAA ostium, which is defined in the plane between the left circumflex artery (straight arrow) and the Coumadin ridge (curved arrow). (c) En-face view of the ostial plane in b shows the LAA ostium in cross-section (arrow), where it is measured. The maximum diameter, minimum diameter, perimeter, and area can be measured.

perimeter (Fig 6, Movie 3). There is a wide range of ostial diameters, from 12.1 mm to 38.8 mm, with a mean $\pm$ standard deviation of $21.9 \text{ mm} \pm 4.1$, and the ostium is generally larger and round in patients with atrial fibrillation (29).

Optimal LAAC device seating is achieved when the atrial end of the device is flush with the plane of the ostium. To accomplish this, the LAAC device is delivered at a certain distance in the LAA from the ostial plane that is referred to as the landing zone. Each specific LAAC device has a different optimal landing zone, according to manufacturer guidelines. At CT, the landing zone is identified on the long-axis LAA view. For the Watchman device, the landing zone is located 10–20 mm inside the LAA from the Coumadin ridge. The landing zone diameters for the Watchman device are measured on an en-face-view CT image obtained at a line that connects the LAA adjacent to the left circumflex artery to the point 10–20 mm inward of the Coumadin ridge (Fig 7,

Movie 4). For the Amplatzer Cardiac Plug and Amulet devices, the landing zone is located 10 mm and 12–15 mm inward of the LAA orifice, respectively, and the diameters are measured on an en-face-view CT image that is obtained at these positions perpendicular to the walls of the LAA (17) (Fig 8). The landing zone for the Amplatzer Cardiac Plug and Amulet devices should be greater than or equal to 10 mm in width, and the distal lobe should be 1.5–3.4 mm larger in diameter than that of the landing zone (30). The maximum landing zone diameter is used for the Watchman device, and a perimeter-derived diameter is used for the Amplatzer Cardiac Plug and Amulet devices. Watchman devices are available with maximum landing zone diameters of 21–33 mm, and Watchman FLX devices are available with maximum diameters of 20–35 mm. Amplatzer Cardiac Plug and Amulet devices are available with perimeter-derived diameters of 16–34 mm and 11–31 mm, respectively.

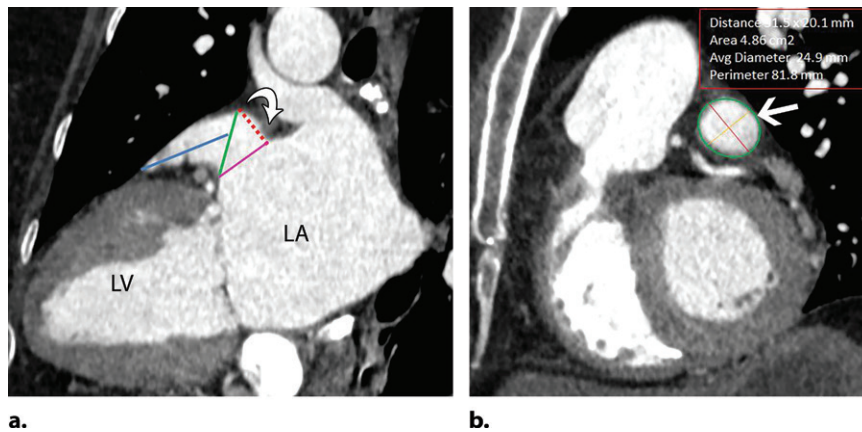


Figure 7. Measurement of landing zone and length of LAA for the Watchman device in a 52-year-old man. **(a)** Vertical long-axis-view CT image of the left ventricle (LV) shows how the landing zone for a Watchman device is identified at a distance of 10–20 mm (red dotted line) distal to the Coumadin ridge (arrow). The pink line is the LAA ostium. The landing zone diameter is measured in the plane between this point and the point where the left circumflex artery is located (green line). The length of the LAA is also measured on the same image from the landing zone to the tip of the dominant lobe (blue line). **(b)** En-face-view CT image shows the cross-sectional view of the landing zone (arrow), where the maximum diameter, minimum diameter, and perimeter are measured.

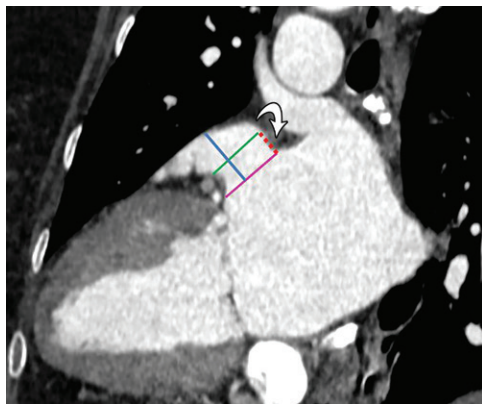


Figure 8. Measurements for the Amulet device in a 52-year-old man. Long-axis-view CT image of the left ventricle shows the landing zone for the Amulet device, which is measured 12–15 mm distal (dotted red line) to the LAA ostium (pink line). The tip of the Coumadin ridge (arrow) demarcates the posterior boundary of the LAA ostium. The landing zone (green line) is perpendicular to the walls of the LAA. The depth of the LAA (blue line) is measured as a perpendicular line from the center of the LAA ostium to the roof of the LAA.

LAA length ranges from 24.9 mm to 85.7 mm (mean length, $49.4 \text{ mm} \pm 9.1$) (31). The length of the dominant lobe is essential for device sizing. A minimum length is required to ensure that the atrial end of the implanted device does not extend into the LA cavity. Insufficient lengths increase the risk of device embolization and pericardial effusion. Device-specific minimum LAA lengths are given in manufacturer guidelines.

At CT, the length is measured as the long-axis view of the LAA. For the Watchman device, the

length of the dominant lobe is measured from the landing zone plane to the tip of the dominant lobe (Fig 7). This length should be larger than the maximum diameter of the landing zone, because the sheath-constrained length of the Watchman device is often similar to the unconstrained diameter of the deployed device (32). For the Amplatzer Cardiac Plug and Amulet devices, the depth of the LAA is measured from the LAA orifice to the roof of the LAA (Fig 8). This length should be greater than 10–12 mm for safe implantation of an Amplatzer Cardiac Plug or Amulet device.

Device Sizing.—Accurate measurements are imperative to optimal sizing of the LAAC device. The consequences of inaccurate device sizing can be devastating. Undersizing can lead to device embolization and peridevice leaks, whereas oversizing can result in device erosion and rupture. Most centers use the landing zone measurements at CT in conjunction with those at TEE to select the appropriate device size. If there is discrepancy between TEE and CT measurements, the larger of the two diameters is used. Measurements at TEE are typically smaller (diameters and lengths 0.7–5.2 mm smaller) than those at CT (29,33,34). There are several potential reasons for this difference between modalities. TEE measurements are made oblique to the true maximal diameter at four angles: 0° , 45° , 90° and 135° , with the largest diameter selected (Fig 9, Fig E4). Because of the curvilinear nature of the LAA, the length of the LAA is often underestimated with TEE. In addition, LAA measurements are often

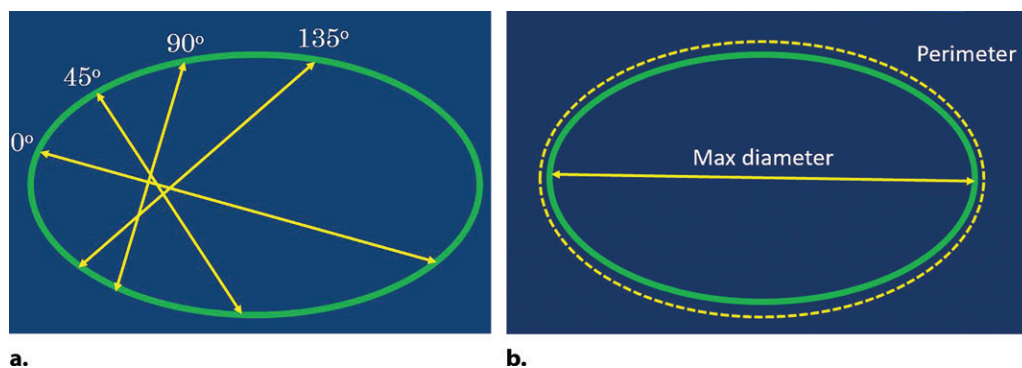


Figure 9. TEE and CT measurements of the LAA ostium. (a) Illustration shows the measurement of the LAA ostium at TEE at four different angles: 0°, 45°, 90°, and 135°. (b) Illustration shows the measurement of the diameter at CT.

smaller at TEE because the patient is dehydrated as a result of preprocedural fasting.

A single-center study (35) of transcatheter LAAC showed that the use of TEE alone would have allowed the inappropriate exclusion of 23% of patients because of undersizing. The use of CT has a device-sizing accuracy of 100% compared with the use of TEE, which is 53% accurate. Accuracy is higher with 3D TEE than it is with 2D TEE (29,36).

In specialty centers in which intracardiac echocardiography is used for procedural guidance, preprocedural TEE is not required, and only CT-based measurements are used (2). CT is associated with higher procedural success than that of TEE (100% vs 82%, respectively) and procedural efficiency, with a lower average number of devices used (1.2 vs 1.8, respectively) (10), fewer guide catheters, shorter procedure times, and lower radiation and contrast material doses (37). The optimal device size is the next size up (3–6 mm larger) from the maximum diameter for the Watchman device and from the perimeter-based mean diameter for the Amplatzer Cardiac Plug or Amulet devices. For example, if a 24-mm-diameter device is identified on the basis of CT, a 27-mm device is implanted. This intentional oversizing by 10%–15% reduces the risk of a peridevice leak. However, it also increases the risk of damage to adjacent structures.

LAA Size, Shape, and Variations.—LAAs vary widely in the size, shape, and number of lobes, which has implications for device selection and procedure planning (17). These characteristics can be evaluated at 2D or volume-rendered 3D CT. The majority (54%) of LAAs have two lobes, 25% have three lobes, and 20% have a single lobe (12).

Four main types of LAA anatomy have been described (27,38,39) and are distinguished by

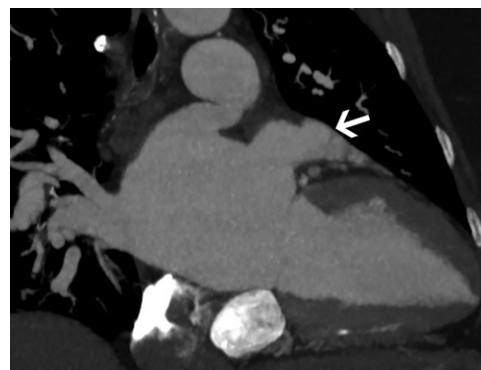


Figure 10. Windsock-type LAA in a 49-year-old man. Coronal reconstructed CT image shows the windsock type of LAA (arrow), which has a single dominant lobe larger than 4 cm long, with an angle of more than 100° from the ostium. Tiny accessory lobes are seen.

the number of lobes, the bend angle, and the presence of a dominant lobe (Table E3). The “windsock” type of LAA is seen in 19% patients and has a single long dominant lobe (Fig 10, Fig E5). It is the type of LAA that allows the easiest measurement and implantation of LAAC devices.

The “chicken wing” type, which is the most common type (48% of patients) of LAA, has a sharp bend (<100°) in its proximal or middle portion or is folded back on itself (Fig 11, Fig E6) (27). Patients with the chicken wing type of LAA have the lowest incidence of stroke (40). This type of LAA increases procedural complexity because of the short LAA length proximal to the bend and the difficulty of navigating the catheter around the sharp bend (32). For this reason, the linear distance from the ostium to the sharp bend is reported at CT (Fig 11b). Because of the sharp bend, the chicken wing tip is located close behind the pulmonary trunk, which is a contraindication to using devices with a hybrid approach. However, there are multiple potential approaches

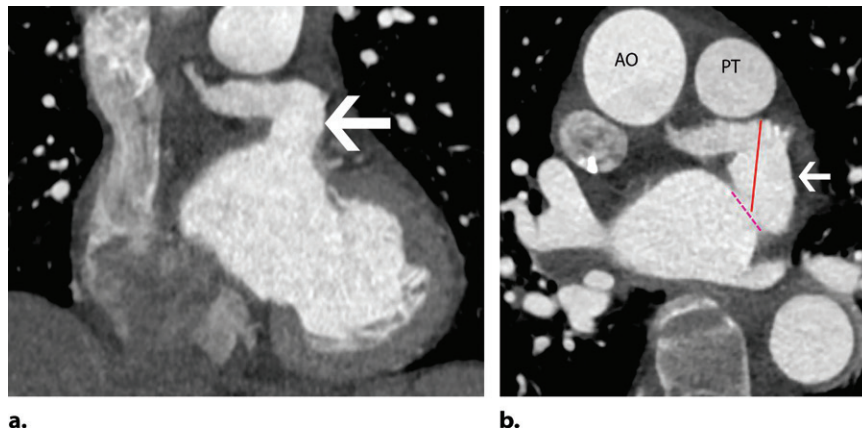


Figure 11. Chicken wing type of LAA in a 56-year-old woman. (a) Coronal 2D image of a chicken wing-shaped LAA (arrow), in which there is a sharp bend ($<100^\circ$) in the proximal segment. (b) Measurement of distance from the LAA ostium (pink dotted line) to the bend (red solid line) in a chicken wing type of LAA. Note that the LAA is located directly posterior to the pulmonary trunk (PT), which makes this a contraindication for the hybrid endocardial-epicardial approach. AO = aorta.

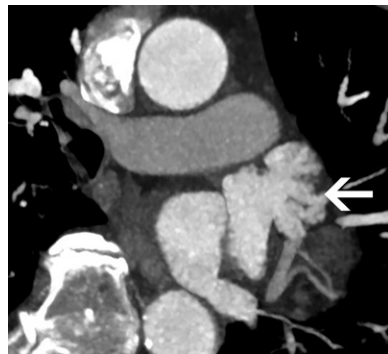


Figure 12. Cactus-type LAA in a 77-year-old woman. Coronal reconstructed CT image shows the cactus type of LAA (arrow), which has a short dominant lobe and small accessory lobes.

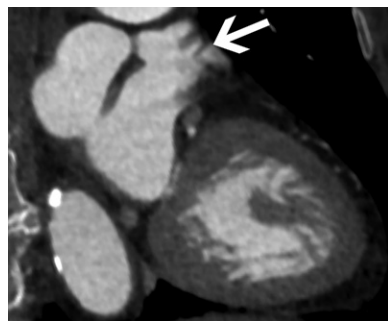


Figure 13. Cauliflower-type LAA in a 61-year-old woman. Reconstructed 2D coronal CT image shows the cauliflower type of LAA, which is short and multilobed, without a dominant lobe or bend.

for implantation, and hence, caution should be exercised when correlating CT and fluoroscopic measurements.

The “cactus” type of LAA (30% of patients) is short, is multilobed (more than two lobes that each measure >1 cm in length), has a dominant lobe, and does not have a bend (Fig 12, Fig E7). As with the windsock type, measurement and implantation are straightforward.

The “cauliflower” type is the least common type (3% of patients) of LAA. It is short, multilobed, and irregular, with thick trabeculations and complex architecture and no dominant lobe or bends (Fig 13, Fig E8). Patients with this type of LAA have an eightfold higher rate of stroke than do those with the chicken wing type of LAA (27). Because of the absence of a dominant lobe and unclear shoulders, identification of the landing zone may be challenging. Also, because of their short length, cauliflower-type LAAs may not accommodate LAAC devices, portending a theoretically higher risk of device embolization.

Other notable types of LAAs include the cone and bilobed types. The cone type of LAA has a single short dominant lobe, with a rapidly tapering transverse diameter from the ostium to the tip (Fig 14, Fig E9). Because of the steep gradient in size, even a minor alteration in position of the landing zone substantially changes the device size. In addition, the tapering increases the pressure on the distal end of the LAAC device, potentially increasing the risk of inadequate seating and device embolization (27,40). The bilobed (ie, “whale tail”) type has two large codominant lobes of similar sizes (Fig 15, Fig E10), which provides two feasible axes of implantation. This type is technically challenging because the common proximal portion of the LAA is often too short to accommodate a device; thus, implantation of two distal devices is potentially required (41).

LAA types are complex and diverse, and an individual LAA may not fit perfectly into one type. Other classification systems exist, including one in which eight types are described: hook, sea horse, finger, knob, wing, spiral, flame, and arrowhead types (42). Regardless of the specific type, a complex shape is often difficult to measure and is associated with a higher risk of a thrombus and procedural complexity (Fig 16) (40,41). LAAs with complex shapes, large sizes (>4 cm), and large lobes and those that extend in

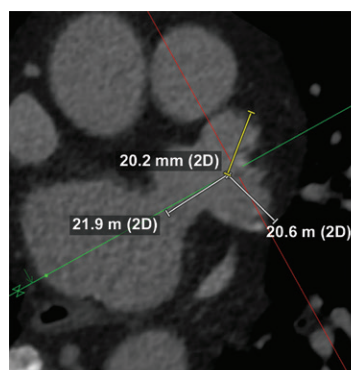


Figure 14. Cone type of LAA in a 63-year-old woman. 2D reconstructed coronal CT image shows an LAA with a cone-type anatomy (arrow), in which there is a rapidly tapering transverse diameter from the base to the apex. Because of this steep gradient, a minor alteration in measurement location can lead to a big change in device size.



Figure 15. Bilobed-type LAA in a 72-year-old woman. 2D reconstructed coronal CT image shows an LAA with a bilobed or whale tail anatomy (arrow). Because of the short proximal portion of the LAA, it is often challenging to implant a device in the common proximal portion. Implantation of two devices may be needed distally in the two lobes.

Figure 16. Complex LAA anatomy types. (a) Coronal reconstructed CT image in a 69-year-old woman shows a complex multi-lobed anatomy that is extending in different directions. Note that there are multiple implantation angles. (b) Axial CT image in a 63-year-old man shows a large (approximately 6 cm) LAA (arrow), which makes the Lariat device unsuitable for use in this patient.



a.



b.

multiple directions with lobes greater than 4 cm apart are not suitable for the epicardial approach.

In LAs without a single long-axis plane in the dominant lobe that is perpendicular to both the ostium and landing zones (ie, chicken wing, cauliflower, bilobed), a modified curved planar reformation technique can be used to measure the landing zone and length (Fig E11, Movie 5). Any variant accessory lobe that is located proximal to the estimated landing zone should be reported, because it can result in a peridevice leak if it is not excluded at the time of device deployment (Fig 17). Large muscular trabeculations extending inferiorly from the LAA to the mitral vestibule have a higher risk of a peridevice leak and perforation, whereas small pits in the antero-inferior ostium may entrap catheters and may not be occluded by the LAAC (4,30).

Coumadin Ridge.—The Coumadin ridge (ie, the left lateral ridge) is an infolding of the lateral atrial wall between the LAA and LSPV that encompasses the ligament and oblique vein of Marshall

(43). The width of the ridge has implications for device sizing and potential complications for disk-and-lobe-type devices. The ridge is usually narrow (≤ 5 mm), especially superiorly, particularly in a cauliflower type of LAA (43). Thinner ridges are thought to increase the risk of LSPV ostial impingement by the device (26). Conversely, wider ridges (>5 mm) can mitigate this risk and allow more flexibility with device oversizing. The Coumadin ridge width is best measured as a linear distance on the 3D volumetric endocardial view CT images (Fig 18) (26). An alternative technique with easier postprocessing is to measure the 2D linear distance from the transverse ostium plane image (Fig 19).

Pulmonary Venous Anatomy and Relationships.

—In most transcatheter LAAC techniques, the delivery catheter is anchored in the LSPV because this stabilizes the guidewire across which the delivery sheath is introduced into the LAA. Thus, the anatomy of the left pulmonary veins and the relationship to the LAA ostium have a

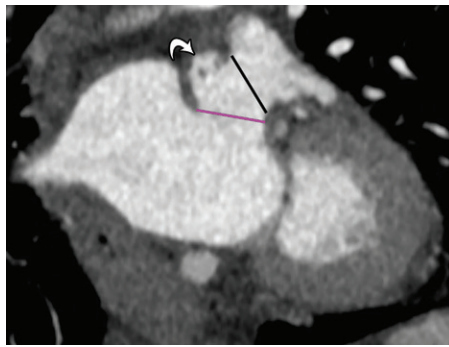


Figure 17. Accessory lobes proximal to the landing zone in a 71-year-old man. Two-chamber CT image shows the presence of a large accessory lobe (arrow) proximal to the landing zone (black line) with a chicken wing shape. The pink line is the LAA ostium. Implantation of the device in this landing zone would result in incomplete LAA occlusion.

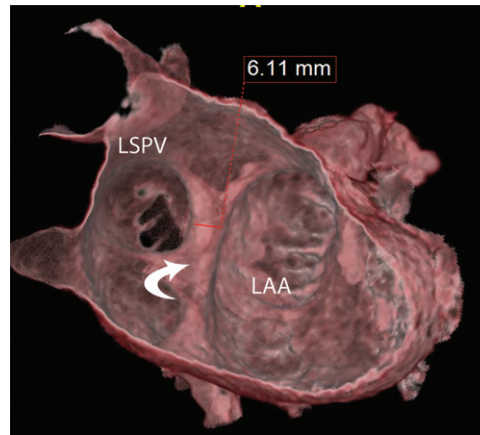


Figure 18. Measurement of the Coumadin ridge in a 39-year-old man. 3D endocardial view of the LA shows the Coumadin ridge (arrow) between the LAA and the LSPV, measuring 6 mm.

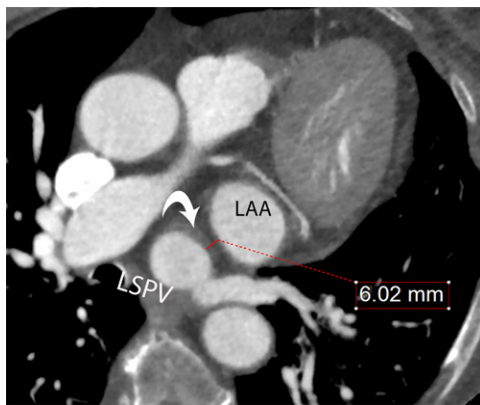


Figure 19. Measurement of the Coumadin ridge in a 39-year-old man. Axial CT image shows the measurement (arrow) of the Coumadin ridge in between the LAA and LSPV.

substantial effect on procedural success (26). At CT, assessment of the pulmonary veins can be done rapidly, with multiplanar reformation or volumetric views of the LA. A spectrum of variation exists in the number, sizes, and branching patterns of the pulmonary veins. The standard number of pulmonary veins is four: two right veins and two left veins. Any deviations from standard anatomy, particularly a common left pulmonary vein trunk or vein stenosis, are reported (Fig E12). With a common left ostium, both the left superior and inferior veins can be affected after the procedure. LAAC can exacerbate any preexisting left pulmonary vein stenosis. When CT is performed for planning pulmonary vein isolation and ablation and LAAC, a more comprehensive assessment of pulmonary vein sizes and branching pattern is needed.

The relationship between the LSPV and the LAA can be assessed at CT, either on multiplanar reformation views or a volumetric endocardial

view from the LA parallel to the Coumadin ridge (44). On these views, the superior margin of the LAA ostium is compared with the superior margin of the LSPV ostium. Three LAA relationships to the LSPV have been described: (*a*) the middle type is the most common (60%–65% of patients), in which the superior margins of the LAA and LSPV are both at the same level (Fig E13); the high type (25%–30% of patients), in which the LAA superior margin is cranial to the LSPV superior margin (Fig E14); and the low type (5%–10%), in which the LAA superior margin is caudal to the LSPV superior margin (Fig E15) (4,45). LAAC device placement in an LAA ostium that is close to the LSPV may interfere with subsequent pulmonary vein ablation and venous return (32). At some centers, practitioners place a precurved wire in the LA rather than anchoring it in the LSPV to perform catheter exchanges and avoid damage to the pulmonary vein. With this procedural modification, preprocedural evaluation of the relationship of the LAA with the LSPV is less important.

Relationship to Other Adjacent Structures.—CT is the optimal modality for providing a 3D assessment of important adjacent structures that may be injured during the LAAC. The pulmonary trunk and left pulmonary artery are posteroinferior to the LAA and are separated by the transverse sinus of the pericardium (Fig E16). The left circumflex artery and great cardiac vein are located in the left atrioventricular groove, inferior to the LAA (Fig 20a, 20b), and have a higher potential for injury when an Amulet device is used (30). Occasionally (in 14% of patients), an S-shaped sinoatrial nodal artery originating from the left circumflex artery may course between the LAA and the LSPV (30) or adjacent to the LAA (Fig 20c). A persistent

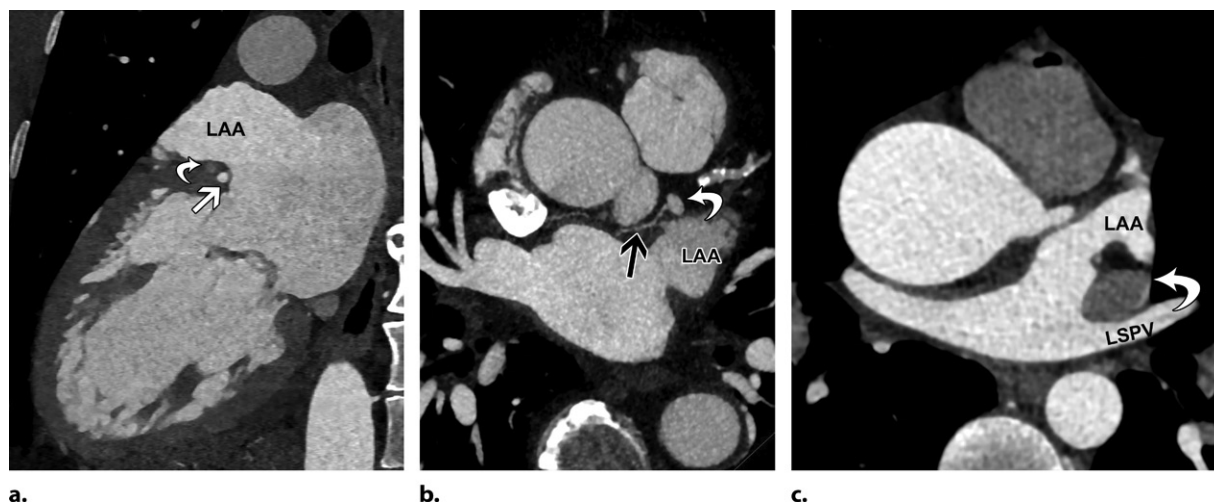


Figure 20. Relationship of the LAA to adjacent structures in three patients. (a) Two-chamber reconstructed CT image in a 37-year-old woman shows the left circumflex coronary artery (straight arrow) and the great cardiac vein (curved arrow), which are located inferior to the LAA. (b) Axial oblique CT image in an 82-year-old man shows the sinoatrial nodal artery (straight arrow), originating from the left circumflex artery (curved arrow) and coursing adjacent to the LAA. (c) Axial oblique reconstructed CT image in a 39-year-old man shows a left-sided superior vena cava (arrow), which is located between the LAA and the LSPV.

left superior vena cava, which is seen in less than 1% of the population, also runs between the LAA and the LSPV (30,43). The Bachmann bundle, an integral part of the atrial conduction system, is located slightly lateral to the ligament of Marshall and encircles the LAA neck (4). Venous coronary bypass grafts to diagonal or marginal branches may be located close to the LAA (30). The left phrenic nerve is located in the fibrous pericardium posterolateral to the LAA, overlying the tip of the LAA in 59% of patients and the neck in 23% of patients (46). In the epicardial approach, the left internal mammary artery and inferior epigastric artery may also be injured (32).

Interatrial Septum.—The interatrial septum is evaluated for abnormalities that preclude LAAC or make it challenging. Such abnormalities include atrial septal defects, a patent foramen ovale, septal aneurysms, and lipomatous hypertrophy (47) (Fig 21). With a patent foramen ovale, a lower transseptal puncture may be needed because of the absence of sealing of the anterosuperior rim (30). Lipomatous hypertrophy results in thick anterosuperior and inferior rims, with constriction of the fossa ovalis. Indwelling septal occluder devices (Fig 21e) and fibrosis from surgical patches make transseptal puncture challenging (30).

Furthermore, site-specific puncture has been increasingly recognized as a key element for procedure success. A puncture location that allows a straight trajectory along the long axis of the LAA perpendicular to its ostium is needed to minimize catheter exchange and mitigate the risk of device tilting or a peridevice leak (48). This usually requires a posteroinferior septal puncture,

with the exact location dependent on the cranio-caudal tilt of the LAA and the specific device (48). The anterosuperior approach has the risk of accidental puncture of the aortic root. From the estimated puncture site or fossa ovalis (Fig 22a), lateral, anterior, and superior distances to the LAA orifice can be estimated at CT (49). Transseptal puncture can be simulated at CT with a virtual guidewire directed from the posteroinferior interatrial septum through the LA and into the LAA ostium along the LAA long axis (Fig 22b, 22c). These images can help the proceduralist visualize the catheter approach and select an appropriate delivery sheath.

Left Atrium.—The size of the LA is a reasonable surrogate for the severity of LA myopathy, which is often present in patients who are undergoing LAAC. LA size can help proceduralists approximate the catheter travel distance from the interatrial septum to the LSPV and the LAA. The LA volume can be calculated with 2D biplane area-length and prolate ellipse methods (Fig E17) or more sophisticated 3D threshold-based methods (50). The presence, position, and size of any LA diverticula or accessory LAAs are also reported because they can theoretically complicate catheter manipulation and device delivery. Diverticula and accessory LAAs are seen in up to 15% of patients and are associated with embolic strokes (30,51). Atrial diverticula are slightly larger than accessory LAAs, have a smooth wall, and are more common on the anterosuperior wall, whereas accessory LAAs have rough internal architecture and are more common in the left lateral wall (Fig E18) (52).

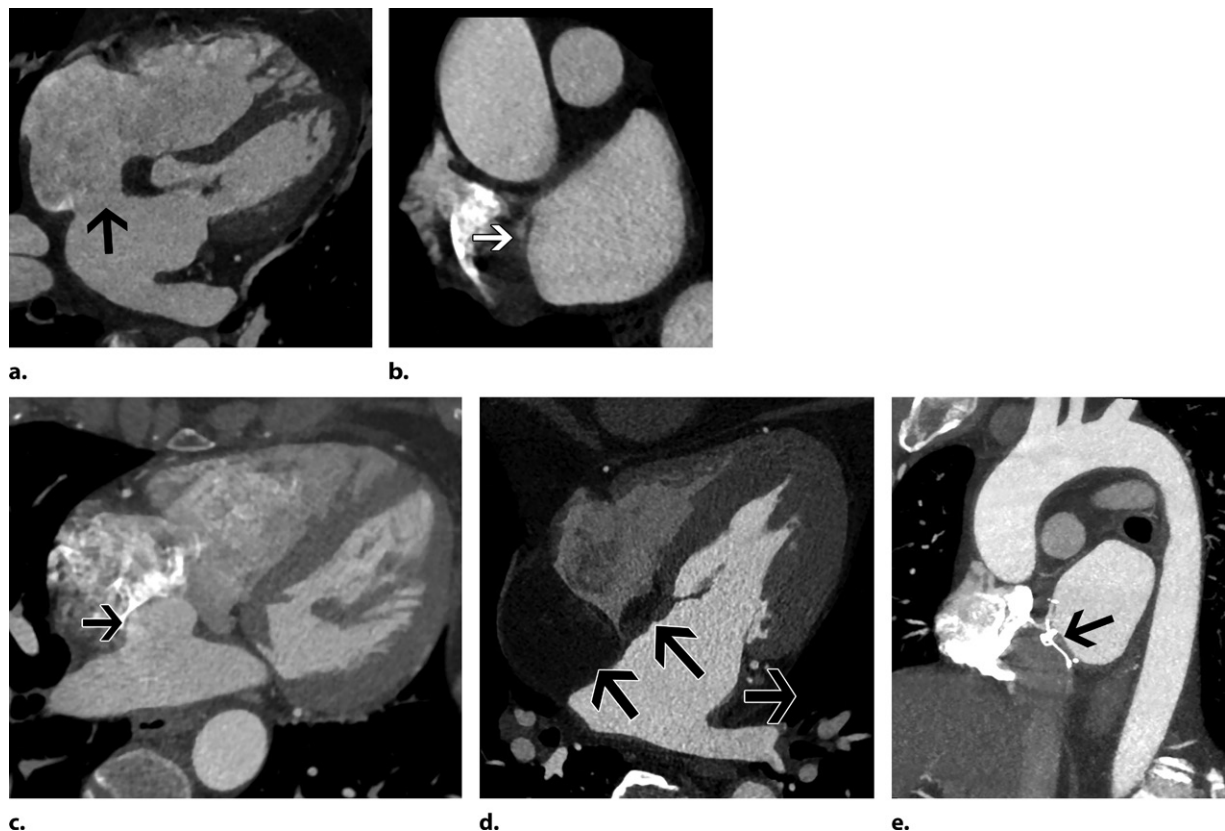


Figure 21. Abnormalities of the interatrial septum in five patients. (a) Axial CT image in a 55-year-old man shows a large secundum type of atrial septal defect (arrow) located in the mid interatrial septum. (b) Short-axis CT image in a 71-year-old man shows a patent foramen ovale, with a small jet of contrast material from the left to the right (arrow). (c) Four-chamber CT image in a 49-year-old man shows a large atrial septal aneurysm (arrow), which is diagnosed when the combined excursion of the interatrial septum in systole and diastole is greater than 1.5 cm. (d) Axial CT image in a 36-year-old woman shows lipomatous hypertrophy of the atrial septum (arrows) measuring larger than 20 mm, with characteristic sparing of the fossa ovalis. (e) Sagittal maximum intensity projection CT image in a 51-year-old man shows an atrial septal occluder (arrow).

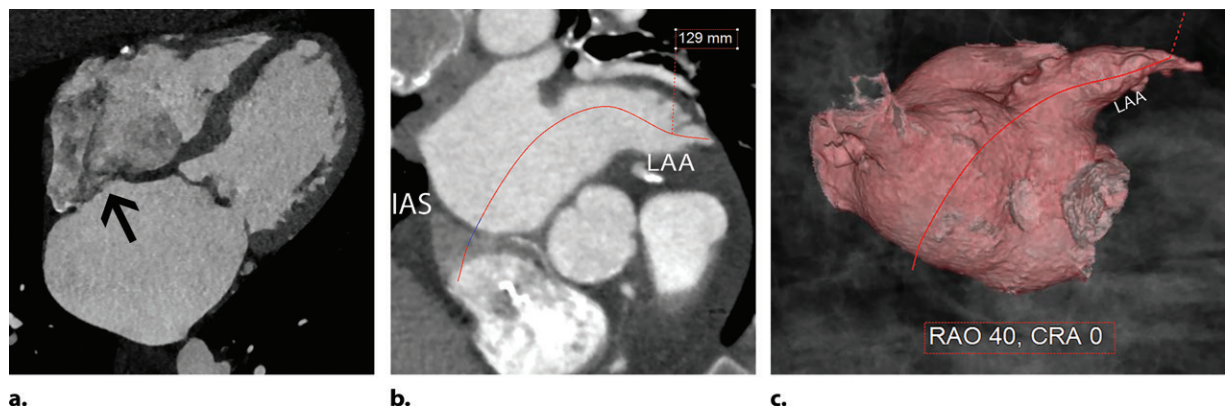


Figure 22. Interatrial septal puncture planning in a 54-year-old man. (a) Four-chamber reconstructed CT image shows the normal appearance of a thinned fossa ovalis (arrow) in the mid atrial septum. (b) Coronal oblique CT image shows a virtual guide of the trajectory of the sheath from the septal puncture into the LAA (orange line). (c) Volume-rendered 3D CT image of the left atrium shows the virtual guide (solid orange line) and the corresponding fluoroscopic angle (dotted orange line). CRA = cranial, IAS = interatrial septum, RAO = right anterior oblique.

Simulated Fluoroscopic Projections.—The LAAC procedure is usually performed with fluoroscopy at a standard angle such as right anterior oblique (RAO) 30/caudal (CAU) 20. This view does not always show the maximal ostium diameter or the LAA length, because it

is difficult to assess the exact anatomy with 2D cine fluoroscopy and contrast material injection. Views that reduce foreshortening of the length of the LAA do not necessarily correspond to the coplanar angle for the ostium. Hence, standardized angles have a high potential for

Figure 23. Coplanar fluoroscopic angles in a 57-year-old man. A coplanar fluoroscopic angulation of the right anterior oblique (RAO) 40/cranial (CRA) 0 view was derived for the plane that is perpendicular to the maximum diameter of the LAA ostium.

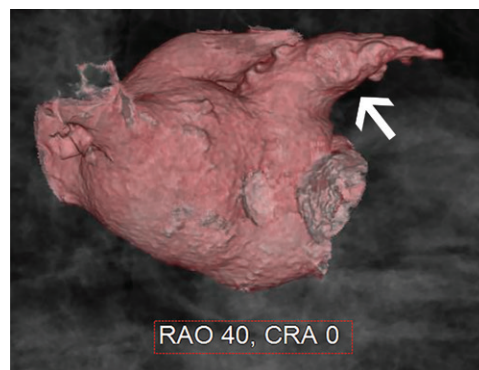
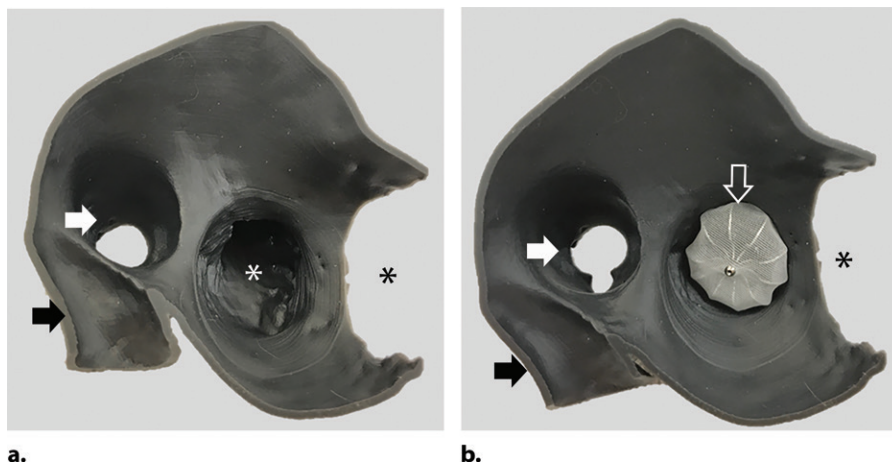


Figure 24. 3D printing. Flexible 3D printed models of the left atrial appendage in a 52-year-old man before (a) and after (b) placement of a simulated Watchman device (open arrow in b). The adequacy of the Watchman device sizing and positioning can be assessed with the models. The left atrial appendage (white * in a), the inferior pulmonary vein (black solid arrow in a and b), superior pulmonary vein (white solid arrow in a and b), and the mitral valve orifice (black * in a and b) are also shown.



incorrect measurement and device sizing and also make LAA cannulation and device delivery challenging. Simulated procedural fluoroscopic coplanar views can be created from volumetric CT images to help with the procedure. With commercially available software, personalized coplanar fluoroscopic angles that correspond to the maximal ostial diameter, maximal landing zone diameter, and maximal LAA length can be generated. The ostial plane view can be used to measure the ostium and navigate the catheter engagement of the ostium (Fig 23). The landing zone plane and the plane of the longest LAA length view can be used to measure the length and to guide device deployment (35). Use of these personalized angles improves device sizing and reduces device waste, procedural time, and contrast material and radiation doses.

3D Modeling and Printing: Virtual Procedural Planning

3D models of the LA and LAA can be created from CT data to plan LAAC procedures. With the use of dedicated software, the LA and LAA are segmented from CT images to create a virtual 3D model. With the use of a stereolithographic file, the virtual model is then printed with a 3D printer to generate a personalized

life-size physical model of the LAA. Different devices of varying sizes and catheters can be tested with these 3D-printed models to evaluate positioning (ie, implantation depth and angulation), anchoring, sealing, and stability (Fig 24). Deformation maps can be used to evaluate the affect on the LAA wall (53). The benefits of 3D modeling and printing for accuracy in device selection and procedural efficiency have been demonstrated in multiple studies (54–56). The use of 3D-printed models correlates better with the final implanted device size than does the use of CT or TEE (54,55), resulting in less device waste, shorter procedure times, lower contrast material and radiation doses, and fewer post-procedural complications such as peridevice leaks and incomplete closures (56). 3D printing models can shorten the learning curve for early operators (35). However, 3D printing uses only static images and is not widely available.

CT Report Template

A standardized reporting process is strongly encouraged for preprocedure CT for transcatheter LAAC. This report should contain the key elements we have discussed: LAA measurements; LAA shape, size, and relationship to adjacent structures; the anatomy of the Coumadin ridge and the inter-

atrial septum; and fluoroscopic angles. A content report template is shown in Appendix E1.

Procedural Imaging

TEE and fluoroscopy are the principle intraprocedural imaging techniques for transcatheter LAAC. In specialized centers, intracardiac echocardiography is used instead of TEE for procedural guidance. The advantages of intracardiac cardiography include its ability to allow direct visualization of the LAA and the septum and to avoid the need for general anesthesia and additional operators (57,58). Via femoral venous access, the guide-wire and delivery sheath are advanced to the right atrium. Under TEE or intracardiac echocardiographic guidance, transseptal puncture is performed (Movies 6, 7), the LA is accessed, the sheath is anchored in the LSPV, and a cannula is placed in the LAA. Fluoroscopy with cine angiography and TEE are then used to examine the LAA size and shape and fine tune the catheter position (Fig 3, Movies 8, 9). The real-time intraprocedural fluoroscopic images can be correlated or fused with preprocedural 3D CT data to improve guidance. The device delivery sheath is then positioned, and the device is deployed in the landing zone with the use of simultaneous fluoroscopy and multiplanar TEE (Movies 10–12). After deployment, device compression of 8%–20%, with the device shoulders in the LAA ostium should be seen in all TEE views (Movies 13, 14). A tug or push-pull test is performed with TEE or fluoroscopy to ensure that the device is anchored. Peridevice leaks can be seen as a Doppler TEE color jet adjacent to the device. For hybrid devices such as the Lariat, a magnet-tipped endocardial guidewire is placed via a transseptal approach at the LAA apex, and a balloon occlusion catheter is placed at the LAA ostium. In addition, through pericardial puncture and epicardial access, a magnet-tipped epicardial guidewire with a pretied suture loop is introduced. The endocardial and epicardial guidewires act as rails for snaring the LAA os, with release of a pretied suture (25).

Postprocedural CT

Complications related to vascular access and transseptal puncture (eg, cardiac tamponade, aortic perforation) are more common in the immediate periprocedural period (59). Complications related to the device include stroke, air embolism, major bleeding, pericardial effusion, a device-related thrombus, a moderate leak, device embolization, and systemic embolization (60). Traditionally, patients start or continue oral anticoagulation therapy for 45 days after transcatheter LAAC, which is thought to be the time needed for device endothelialization. At 45 days

after the procedure, TEE is performed to exclude an intracardiac or device-related thrombus or a substantial leak (>5 mm). If there is no complication, warfarin is discontinued and clopidogrel is added. Contrast-enhanced MRI can allow localization of the LAA occluder devices and detection of leaks but is limited by artifacts and long imaging times (61). CT is increasingly used to clarify equivocal TEE findings or to characterize the complications that are identified at TEE. CT can replace TEE for characterization of postprocedural complications, specifically for thrombi and leaks (62). Higher tube voltages are used at postprocedural CT to mitigate device-related metallic artifacts. The device is evaluated in multiple dedicated planes, with images obtained by centering on the screw hub and generating planes perpendicular to the coves of the parachute in the Watchman device and perpendicular to the disk in the Amplatzer Cardiac Plug device (62–64) (Fig 25, Movies 15, 16). At CT, a normal LAAC device is seated in the LAA and sealed to its wall, without any rotation around its central axis. The Watchman device has a compression size of 10%–20% compared with the original device size. The lobe of the Amplatzer Cardiac Plug device is located two-thirds of the way distal to the left circumflex artery, with its axis in line with the LAA neck axis (63). Typically, after 45 days, there is no contrast material opacification either in or around the device or distally in the LAA due to endothelialization. Equal contrast enhancement between the LAA and LA indicates the absence of endothelialization. Incomplete endothelialization is diagnosed when the contrast enhancement in the LAA is lower than that in the LA by at least 50 HU (63). However, recent studies have shown that complete thrombosis in the device is seen in only 27% of patients, even at 6 months, and is seen more often in windsock- and cauliflower-type LAAs (62). Endothelialization cannot be assessed if there is a peridevice leak. The presence of any remnant LAA or a lobe between the sealing part of the device and the plane of the LAA ostium is assessed. For successfully placed endocardial and epicardial devices, a “waist” is seen in the LAA, with no contrast material in the LAA (Fig 26).

Pericardial Effusion

Pericardial effusion may be due to either direct pericardial injury overlying the thin-walled LAA during deployment or injury to the adjacent structures (eg, LSPV), which may then bleed into the pericardium (65). Ninety percent of pericardial effusions occur within 24 hours after LAAC (65). Although they are typically evaluated with echocardiography, pericardial effusions can be

Figure 25. Normal CT appearance after placement of a Watchman device in a 73-year-old man. (a) Volume-rendered 3D reconstruction CT image obtained 60 days after implantation shows the Watchman device (arrow). (b) Coronal contrast-enhanced CT image shows no enhancement in the device (arrow), which indicates that endothelialization has occurred, and no peridevice leak. (c) Cross-sectional reconstructed CT image shows the device hubs and normal appearances of a thrombus (arrow) in the device.



a.



b.



c.

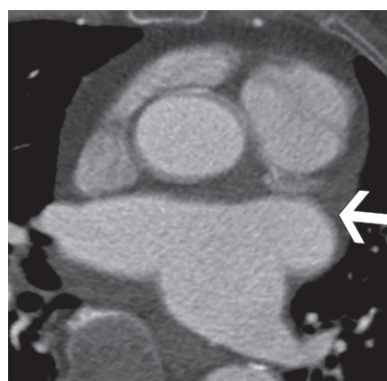


Figure 26. Normal postprocedural CT appearance after placement of the Lariat device in a 59-year-old woman. Axial CT image shows ligation of the LAA (arrow) and no contrast material opacification of the LAA.

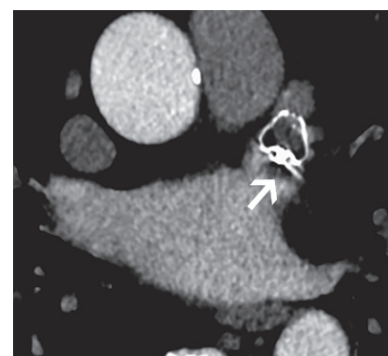


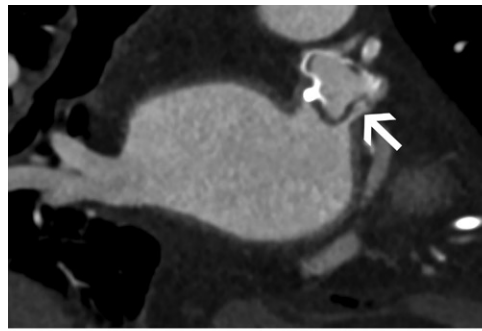
Figure 27. Device-related thrombus in a 64-year-old woman. Axial CT image shows a hypoattenuating lesion on the surface of the Watchman device (arrow) that persisted in the delayed phase (not shown), which is consistent with a device-related thrombus.

characterized at CT by observing the volume and character of the fluid in the pericardial sac (Fig E19). High-attenuation pericardial fluid suggests hemopericardium. Treatment options include performing pericardiocentesis or a pericardial window, suturing an LAA tear, or redeploying an LAAC device (65).

Device Embolization

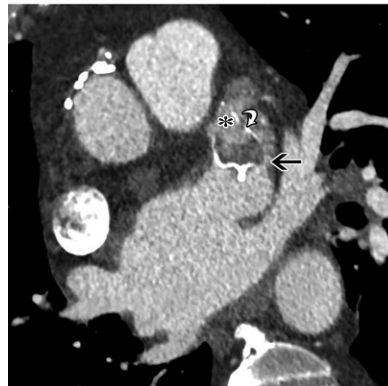
Device embolization is a rare complication (66). Risk factors include undersizing, oversizing,

noncoaxial alignment, and shallow placement. Complex LAA shapes and sizes, a wide ostium, a large landing zone, and a shallow LAA depth are LAA-related risk factors. Device embolization typically occurs during the procedure; thus, CT is rarely required for diagnosis. Larger devices embolize to the LA or left ventricle or get trapped in the mitral or aortic valve, whereas smaller devices embolize to the descending aorta (66). Embolized devices can be retrieved percutaneously (65).



a.

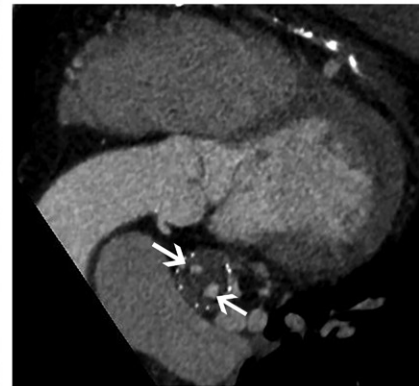
Figure 28. Peridevice leak in four patients. (a) Coronal reconstructed CT image in a 59-year-old man with a Watchman device shows incomplete sealing of the device in the LAA wall, resulting in a peridevice leak lateral to the device (arrow), which results in free flow of contrast material inside the device. (b) Reconstructed coronal CT image in a 63-year-old man with a Watchman device shows off-axis placement of the device (white arrow) with a peridevice leak laterally (black arrow). There is flow of contrast material in the device (*) and distally in the LAA apex. (c) Axial CT image in a 47-year-old man shows a large leak measuring 11 mm around the lateral aspect of the device (arrow). Contrast material is also seen in the distal LAA beyond the device. (d) Fabric leak with two contrast channels is seen within the device material (arrows).



b.



c.



d.

Device-related Thrombus

A thrombus on the LA surface of the device is an uncommon complication of LAAC (65). Risk factors include incomplete LAA occlusion, deep implantation, large LAA diameter, high CHADS₂ (congestive heart failure, hypertension, age ≥ 75 years, diabetes mellitus, stroke or transient ischemic attack) score or CHA₂DS₂-VASc (congestive heart failure, hypertension, age ≥ 75 years, diabetes mellitus, stroke or transient ischemic attack, vascular disease, age 65–74 years, sex category [female]) score, and a low ejection fraction (64). With the Amulet device, thrombus commonly develops near the superior edge of the disk, adjacent to the Coumadin ridge (65). At CT, the thrombus is seen as a hypoattenuating lesion on the surface of the device (Fig 27). The persistence of the filling defect in the delayed phase helps in distinguishing a thrombus from stasis. Although early studies (67) showed no increased risk of stroke with a device-related thrombus, recent studies (68,69) suggest a four- to fivefold increase in thromboembolic events. Oral anticoagulants or low-molecular-weight heparin are used for treatment (65).

Peridevice Leaks and Incomplete LAAC

A peridevice leak is commonly seen in up to 68.5% of patients after LAAC (7,8,13,25). At CT, a *peridevice leak* is defined as the presence of a contrast-enhancement trail adjacent to the device (64). Contrast enhancement may also be

seen in the device and in the distal LAA. Common causes of peridevice leaks are a *peridevice gap*, which is the failure of the Watchman device to expand against the LAA in the landing zone (Fig 28a); off-axis positioning of the Amplatzer Cardiac Plug or Amulet devices (Fig 28b); and failed endothelialization (70,71). Tissue remodeling, a highly elliptical orifice, a large landing zone, large LA size, and a non-chicken-wing type LAA (especially windsock type) are other risk factors (25,64,65,72). A peridevice leak can be minimal (<1 mm), mild (1–3 mm), moderate (4–5 mm), or severe (>5 mm). A peridevice leak larger than 5 mm is considered significant and is also called *incomplete closure* of the LAA (Fig 28c). CT is more sensitive than echocardiography for detection of peridevice leaks (68), especially for detection of submillimeter marginal leaks, transfabric leaks, and defects of endothelialization (25) (Fig 28d). With incomplete closure or endothelialization, there is free flow of contrast material into the device and distal LAA, without thrombus formation (7,73) (Fig 29, Fig E20). Defects of endothelialization disappear within 45 days to 6 months after LAAC, whereas other mechanisms persist. Hence, follow-up CT later is prudent to identify persistent peridevice leaks. There is an increased risk of thrombus formation with a peridevice leak, but there is no significant correlation between peridevice leaks and thromboembolic events (67,70,71,74).

Incomplete closure and leaks can be seen in 5%–14% of procedures in which the Lariat device was used (25,75). Acute leaks (during the procedure) most commonly occur because of a suboptimally tightened suture (25). Early (<6 months) and late leaks are due to slippage of the knot, misalignment of the magnets or suture, and selective ligation of one lobe in a multilobar anatomy (25). At CT, incomplete ligation is characterized by persistent free flow of contrast material into the LAA, typically in a central location (ie, the “gunny sack” effect) (25) (Fig 30, Fig E21). Lariat leaks have been shown to cause a higher risk of stroke, particularly when the leak is small (<5 mm) (25,76).

Peridevice leaks smaller than 5 mm can resolve spontaneously with endothelialization (65), but patients with leaks that are larger than 5 mm need oral anticoagulation therapy. Irrespective of the size of a peridevice leak, an incomplete or absent thrombus inside the device also warrants anticoagulation therapy (25). A large peridevice leak in endocardial devices is closed with endovascular coils or vascular plugs (25), whereas concentric leaks after LAAC with a Lariat device are closed by repeating the procedure with a Lariat device or using an Amplatzer septal occluder (Abbott) (77).

Device Erosion

Erosion of the device through the LAA and into the adjacent pulmonary artery is extremely uncommon. It can be seen several weeks or months after the procedure and can lead to cardiac tamponade (78). Device oversizing and increased proximity of the pulmonary artery to the LAA are thought to precipitate device erosion. CT can be used to identify the location of the device and the location of bleeding.

Conclusion

Transcatheter LAAC is a rapidly growing option for prevention of stroke in patients with nonvalvular atrial fibrillation. Although TEE has been the reference standard imaging modality for pre- and postprocedural imaging, cardiac CT allows more accurate delineation of the LAA anatomy and sizing of the device, while providing an excellent ability to detect contraindications before the procedure. CT is also helpful in examining the device integrity and complications during follow-up after the procedure.

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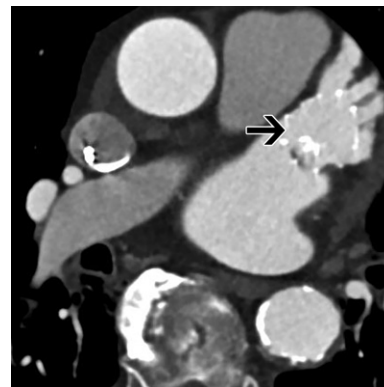


Figure 29. Incomplete closure due to absence of endothelialization in an 80-year-old man 60 days after implantation of a Watchman device. Axial CT image shows the absence of a thrombus and extensive contrast material in the device (arrow), which is consistent with a complete absence of neoendothelialization.



Figure 30. Incomplete closure in a 53-year-old man after placement of a Lariat device. Two-chamber CT image shows free flow of contrast material in the LAA (arrow) as the result of incomplete ligation of the LAA.

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